Optically induced reconfigurable three-dimensional nonlinear photonic lattices in anisotropic media

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Abstract: *By two simple optical holographic approaches, we experimentally investigate the formation and dynamics of three-dimensional (3d) reconfigurable photonic lattices in SBN:Ce photorefractive crystals, and compare the generated structures with computer simulations.*

Introduction

Photonic crystal structures, especially periodic nonlinear photonic lattices in anisotropic media, are subject of active research due to their versatile promising applications [1]. In view of possible fascinating nonlinear effects originating due to the interplay between nonlinearity and various lattice geometries as well as periodicities, different approaches are adapted to form mostly two-dimensional (2d) photonic lattices in photorefractive media like SBN:Ce [2, 3, 4]. Since the photonic lattice geometry in higher dimensions influences the inter-site coupling and wave scattering drastically [4], it is also important to investigate 3d nonlinear photonic crystal structures in anisotropic media and the beam dynamics in such lattices.

Among different fabrication techniques for photonic crystal structures, it has been shown that all fourteen Bravais lattices in three dimensions can be fabricated by holographic approach either by a single-step interference of multiple beams or by two beam multiple exposure approach [5, 6]. Compared to the conventional four beam interference for the fabrication of 3d photonic crystal structures, the two beam multiple exposure holographic approach by rotating the recording sample only about a single axis is very simple in terms of experimental complexity [6]. First, we experimentally generate reconfigurable 3d photonic lattices, exploiting the simplicity of this method. Secondly, making use of the versatility of programmable Spatial Light Modulators (SLM) [2, 3] based on computer-generated phase engineered structures that represent multiple exposure holographic intensity patterns, instead of using separate diffractive optical elements [7], we simplify our multiple beam interference technique in order to generate similar 3d photonic lattices.

Dual Beam Single Axis Triple Exposure Technique

In general, for two-beam interference, the intensity distribution is given by [6],

$$I = E_1^2 + E_2^2 + 2E_1E_2e_{12}\cos\left[\left(\mathbf{k}_1 - \mathbf{k}_2\right)\cdot\mathbf{r}\right], \qquad (1)$$

where E_1 and E_2 are the complex amplitudes, $\mathbf{k}_1$ and $\mathbf{k}_2$ are the wave vectors of the interfering beams, and e_{12} is the polarization cross term between the two interfering beams, respectively. Assuming that both beams are linearly polarized in the same direction, after three exposures, the total intensity distribution is given by, $I = I_{12} + I_{13} + I_{14}$.

$$I = 6 + 2\left\{\begin{aligned}&\cos\left[\left(\mathbf{k_1}\text{-}\mathbf{k_2}\right).\mathrm{r}\right] + \cos\left[\left(\mathbf{k_1}\text{-}\mathbf{k_3}\right).\mathrm{r}\right]\\ &+\cos\left[\left(\mathbf{k_1}\text{-}\mathbf{k_4}\right).\mathrm{r}\right]\end{aligned}\right\} \qquad (2)$$

As shown in Fig.1a, $\mathbf{k_1}$ is the wave vector of the first beam common to all the three exposures. For the purpose of single axis rotation, $\mathbf{k_1}$ is chosen to be normal to the recording medium. The wave vectors $\mathbf{k_2}$, $\mathbf{k_3}$, and $\mathbf{k_4}$ represent angularly displaced second beam from the normal respectively for the first, second, and third exposure.

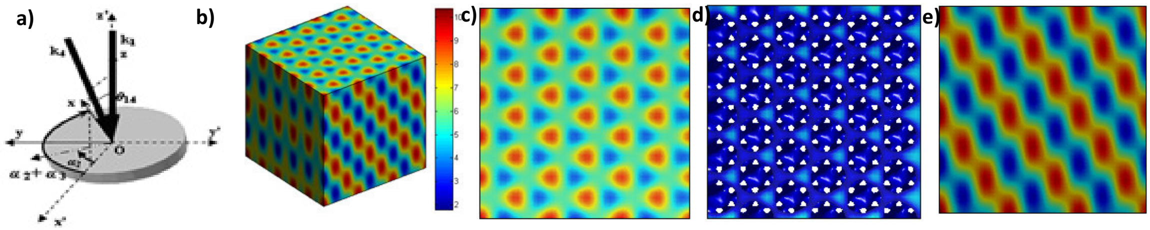

Fig. 1: a) Schematic arrangement of the interacting beams. b) fcc lattice. c) fcc lattice (111) plane. d) fcc lattice (111) plane with regions of intensity above 30% of maximum and lattice constant shifted by 0.55. e) fcc lattice $(11\bar{2})$ plane.

From the grating vectors of the interfering terms of eq. 2, the angle θ_i between the beams and the rotation angles, α_i (α_1, $\alpha_1+\alpha_2$, and $\alpha_1+\alpha_2+\alpha_3$ respectively for first, second, and third exposure) could be computed [6]. Using these values, different three dimensional photonic structures could be simulated, relating the grating vector to the reciprocal lattice vector of the crystallographic lattice geometry [6], for example face centred cubic (fcc) lattice as given in Fig. 1b-e. For fcc lattice, the computed values are, $\theta_1=\theta_2=\theta_3=38.94^o$, $\alpha_1=0^o$, $\alpha_1+\alpha_2=120^o$, and $\alpha_1+\alpha_2+\alpha_3=240^o$. The experimentally realized photorefractive nonlinear 3d photonic lattice in an externally biased (1.5kV/cm) SBN:Ce (5mmx10mmx5mm) photorefractive crystal at a wavelength of $\lambda = 0.532$ µm are shown in Figs. 2a and 2b. Lattice forming beams were ordinarily polarized, while the broad plane wave used to probe the lattice was extraordinarily polarized, experiencing maximum refractive index modulation.

Single Step Optical Induction Approach

In this approach, by means of a programmable phase only SLM, using a phase engineered pattern we modulate the phase of a plane wave to form the required beam configuration for the multiple beam interference in order to generate three dimensional photonic lattices. Both four-beam and seven-beam configurations are experimentally done to generate 3d photonic crystal structures as given in Fig. 2c-e.

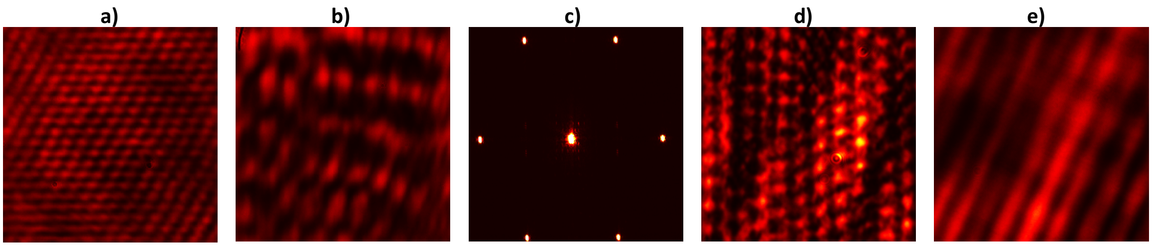

Fig. 2: (i) Dual beam single axis triple exposure technique: a) and b) respectively of (111) and $11\bar{2})$ lattice planes of fcc formed in SBN:Ce. (ii) Single step optical induction approach: c) Beamlets at the Fourier plane. d) and e) 3d lattice planes generated in SBN:Ce, perpendicular to the direction of propagation axis of the central beam and parallel to it respectively, by the interference of four beams.

Conclusion

We have experimentally generated the optically induced three-dimensional nonlinear photonic lattices in an externally biased SBN:Ce photorefractive crystal. These lattices in higher spatial dimensions enable to investigate nonlinear beam propagation in them for promising nonlinear applications such as slow light, localized states or 3d tunneling effects.

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